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An alternative approaches to predict flashover voltage on polluted outdoor insulators using artificial intelligence techniques

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ABSTRACT

This paper presents an alternative approach for predicting critical voltage of pollution flashover by using Artificial Intelligence (AI) technique. Data from experimental works combined with the theoretical results from well-known theoretical modelling are used to derive algorithm for Artificial Neural Network (ANN) and Adaptive Neuro-fuzzy Inference System (ANFIS) for determining critical voltage of flashover. Series of laboratory testing and measurement are carried for 1:1, 1:5 and 1:10 ratios of top to bottom surface salt deposit density on cup and pin insulators. Insulators variables such as height H, diameter D, form factor F, creepage distance L, equivalent salt deposit density (ESDD) and flashover voltage correction are identified and used to train the AI network. Comparative studies have evidently shown that the proposed (AI) technique gives the satisfactory results compared to the analytical model and test data with the Coefficient of determination R-Square value of more than 97%.

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1. INTRODUCTION

The exposure of insulator surface to various conditions of environmental and pollution depositions is inevitable in almost all energy systems [1-4]. Flashover on outdoor insulator occurs due to increase of electrical stresses on the transmission line combined with the high pollution level [5]. Critical voltage of flashover on polluted outdoor insulator surface is one of the important parameters for accessing reliability of a power system. Flashover prediction especially using numerical approaches have been always become a topic of interest among researchers [6]. Artificial intelligence can be used to analyses degree of pollution level, surface tracking and erosion as well as estimation of flashover occurances. In this work, data from the experimental works combined with the well- established theoretical models are utilized to develop an enhanced prediction algorithm via Artificial Neural Network (ANN) and Adaptive Neuro-fuzzy Inference System (ANFIS). Flashover voltages of polluted insulator for 1:1, 1:5 and 1:10 ratios of top (T) and bottom (B) surface ESDD on cup and pin insulators (porcelain and glass) are investigated.

2. MATHEMATICAL MODELS

The process of contaminated insulators flashover has been carefully studied by several researchers. The simplest model of the pollution layer is the one developed by Obenaus which consists of an arc which shorts the dry zone in series with an equivalent resistance in the wetted area [7, 8]. Applying Ohm's law to the circuit of Figure 1.

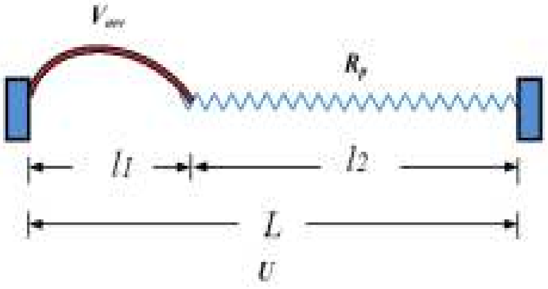


Figure 1. Equivalent circuit model of Obenaus

The voltage across the insulator is given by:

$$U = \frac{l_1 N}{I^n} + k l_2 R_p I \tag{1}$$

in which l_1 is the arc length, L is the insulator creepage distance, R_P is the contamination layer resistance per cm, I is leakage current and N is the arc constants. In many cases, Rp can always be substituted with the conductivity, σ of the layer of pollution. Wilkins [9] has introduced an expression (2) for the coefficient, k to represent resistance of the pollution layer taking into account the current concentration at the foot point of arc.

$$k = 1 + \frac{n+1}{2\pi F n} \cdot ln\left(\frac{L}{2\pi F R}\right) \tag{2}$$

where R is the arc foot radius in cm and F is the form factor. The critical voltage, U_c and current, I_c can be determined by using expression (3) and (4) respectively:

$$U_c = \frac{A}{n+1}(L + \pi \cdot D \cdot F \cdot k \cdot n)(\pi \cdot D \cdot \sigma \cdot N)^{\frac{-n}{n+1}} \tag{3}$$

$$I_c = (\pi \cdot D \cdot \sigma \cdot N)^{\frac{1}{n+1}} \tag{4}$$

where D is the insulator diameter, F is form factor,

3. EXPERIMENTAL WORK

3.1. Test insulators

The insulators models are porcelain (XP-70) and glass (LXY-70) as shown in Figure 2. The clean and polluted insulators were tested under different parametric voltage sources. The dimension of samples are given Table 1, in which H is the insulator height, D is the insulator diameter, L is the leakage distance and F is the form factor.

(a) (b)

Figure 2. Insulator specimens, (a) Porcelain XP-70, (b) Glass LXY- 70

Table 1. Dimensions of the insulator specimens

Sample	Type	Materials	H/cm	D/cm	L/cm	F
A	LXY- 70	Glass	14.6	25.5	31	0.89
B	XP-70	Porcelain	14.6	25.5	29.5	0.736

3.2. Experimental setup

The experimental procedure were carried out in a different multifunctionalartificial chamber approximately 1.2 m ×1.0 m and circuit arrangement is illustrated in Figure 3. The voltage was measured through AC divider of capacitive voltage while leakage current measured through shunt resistance of 10 k ohm. The data acquisition monitoring system is consisting of personal computer (PC), DAQ card and LabVIEW software.

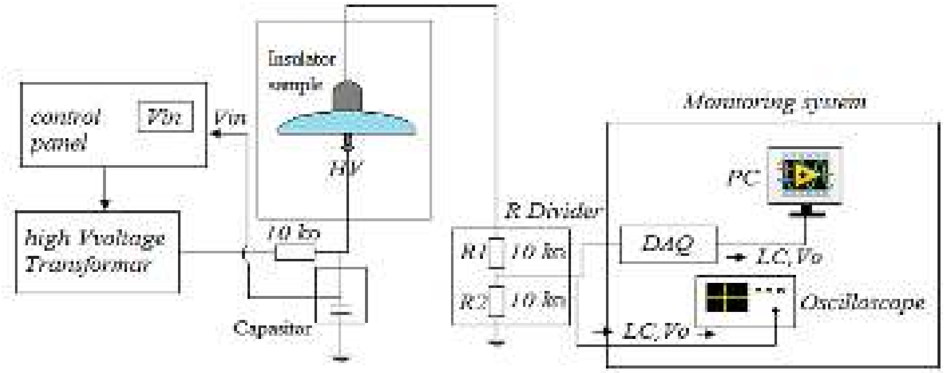


Figure 3. Block diagram of the experimental setup

3.3. Test procedure

Prior to the test, the insulator was first carefully cleaned using alcohol and water with conductivity lower than 10 µS/cm. Pollution suspension is prepared by mixing an appropriate ratio kaolin with Sodium Chloride (NaCl) in water to achieve the desired conductivity level as described in [10, 11]. The salinity of the pollution layer on the insulator is then determined using a conductivity meter. The contamination was applied according to solid layer method using brush before allowed to dry naturally for 24 hours. A sprayer is used to wet the polluted insulator sample under normal ambient condition with temperature of 25°C and humidity of 91%. To prepare a non-uniform polluted insulator ($R\neq1$), the top and bottom sides were polluted separately in terms of different equivalent salt deposit density ($ESDD_T$ and $ESDD_B$), the average equivalent salt deposit density ESDD should be satisfied by [12]:

$$ESDD = \frac{ESDD_T \cdot A_T + ESDD_B \cdot A_B}{A_T + A_B}, \tag{5}$$

where $ESDD_T$ represents the equivalent salt deposit density of the top side, $ESDD_B$ represents the equivalent salt deposit density of bottom side, A_T is the top side surface area, A_B is the bottom side surface area and r is the ratio of pollution degree in the top side to bottom side on the non-uniform polluted insulator.

3.4. Flashover voltage (FOV) measurment

Severity of contamination was classified as four level are clean, light, moderate and heavy in different ESDD values as shown in Table 2. The tests of flashover were carried out on samples of cup and pin (porcelain and glass) insulators. Samples of wet polluted insulators were subjected to AC voltage source, which gradually increase until flashover occur. The results of the flashover measurement are tabulated in Table 2. The average of flashover voltage was calculated as [13]:

$$U_{FO} = \frac{\sum_{i=1}^{N} U_i}{N} \tag{6}$$

where U_{FO} is flashover voltage, $U_i$is flashover voltage carried out at i test, and N is number of valid tests.

Table 2. Measured voltages and current of flashover

Insulator Type		LXY- 70				XP-70			
Flashover Voltage	ESDD (mg/cm^2)	*r*							
		1/1	1/5	1/10	1/15	1/1	1/5	1/10	1/15
U_{FO} (kV)	0.03	23.1	29.49	32.25	33.86	26.95	34.99	38.45	40.48
	0.05	19.32	24.67	26.97	28.32	26.95	34.98	38.45	40.48
	0.1	13.33	17.02	18.61	19.54	20.96	27.22	29.91	31.49
	0.15	9.81	12.53	13.69	14.38	15.08	19.58	21.51	22.65
	0.2	8.67	11.07	12.10	12.71	12.22	15.87	17.44	18.36
	0.25	7.36	9.40	10.27	10.79	10.99	14.27	15.69	16.51
	0.3	7.082	9.04	9.89	10.38	8.98	11.66	12.81	13.49
	0.35	6.57	8.39	9.17	9.63	8.31	10.78	11.86	12.48

Based on the Table 2, the results of tests show that the U_{FO} of polluted insulators is decreasing as the severity of pollution is increasing. The relationship between the flashover voltage of the polluted insulator and ESDD can be expressed in (7) [14].

$$U_{FO} = x\, ESDD^{-y} \tag{7}$$

where *x* is constant related to the dimensions of the insulation, type of applied voltage and the conditions surrounding the insulator and *y* is the exponent that characterizes the impact of pollution. In non-uniform pollution case, The U_{FO} of insulators are affected by ratio of $ESDD_T$ to $ESDD_B$ and expression (7) can be re-write as:

$$U_{FO} = x\, ESDD^{-y}.C \tag{8}$$

where C is correction of flashover voltage under non-uniform pollution and A is the coefficient ranges from 0.29 to 0.47 for cup and pin insulators. The correction of flashover voltage *C* value of glass and porcelain insulators under different non-uniform pollution conditions.

4. DETERMINATION OF ARC CONSTANTS

The voltage across the arc have expressed in terms of Ayrton's equation as:

$$E_{arc} = N I_{arc}{}^{-n} \tag{9}$$

where N and n are the static and dynamic arc constants respectively. Here, E_{arc} represents the arc voltage gradient and *I* represent arc current. Most works [15-20] on polluted insulators uses characteristic arc constants N and n for various atmospheres if the discharge propagates through a humid atmosphere or in water vapor as tabulated in Table 3.

Table 3. The constants N and n

Author	N	n	Year
Dixit et al	68	0.65	2009
Y. Sabri	168	0.325	2010
Yawei Li	112.1(T) 65.8(B)	0.82(T) 1.13(B)	2014

The arc constants for insulator A and B were derived from experimental data, while the mathematical relation between E_{arc} and I_{arc} was detemined by applying the regression method. In this study, the voltage and current arc were measured on a realcup-pin pollution standard insulators. The voltage and current of arc measured between pin as a high voltage electrode and 3mm steel rod as another electrode located on the head of rib as illustrated in the Figure 4. Two arc length up to rib 2 and rib 3 representing 7 cm and 10 cm from metal conductor respectively, were chosen to be tested under different pollution levels ranging from 0.01 up to 0.35 mg/cm^2.

The flashover voltage against ESDD experimental data can be used to compute the constants of arcmathematically for different ESDD using least square method. The results of test voltage and current of arc under different pollution severity obtained from two samples insulators are substituted in (9) resulting in to total of 46 equations for each insulator type. To obtain the constants of arc N and n, 46 equations were simulated using ‘lsqnonlin’ function from the Optimization tool box in MATLAB.

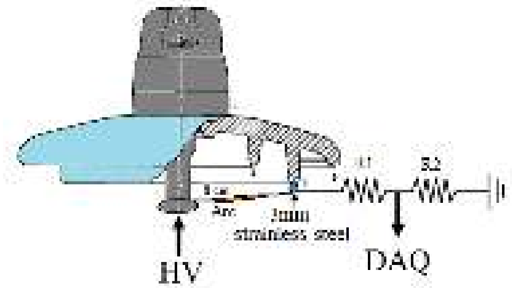


Figure 4. Schematic representation to study voltage-current behaviour of arc

5. DERIVATION OF ARTIFICIAL INTELLIGENCE (AI)

5.1. Artificial neural network model (ANN)

The severity of deposited pollution on the surface of insulators under uniform and non-uniform condition and the insulators dimension were studies in attempt to derive prediction of insulators flashover voltage using ANN [21-25]. The ANN was simulated using MATLAB R2017a Neural Network Toolbox. The six variables representing the insulator high *H*, diameter *D*, form factor *F*, creepage distance *L*, equivalent salt deposit density *ESDD* and flashover voltage correction under non-uniform Pollution *C* were used as input of ANN and insulator flashover voltage as the output. The structure of ANN showed in Figure 5(a). The mathematical relationship between theinput and output of ANN can be expressed in the function form as:

$$U_{FO} = f(H, D, F, L, ESDD, C) \quad (10)$$

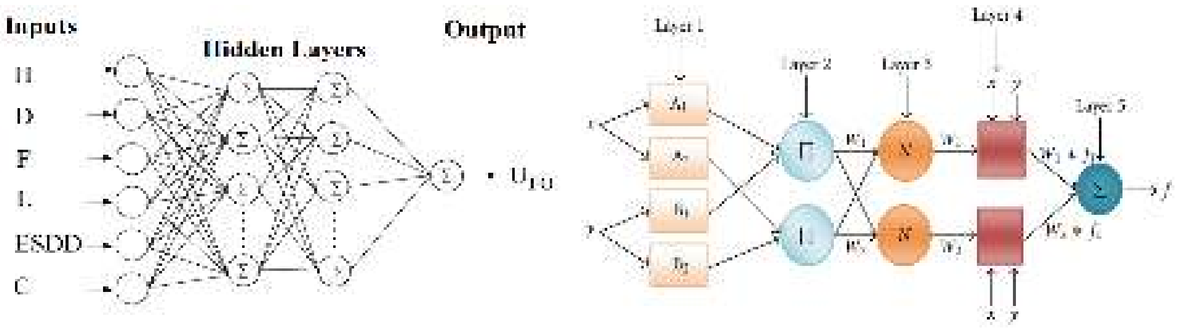
5.2. Adaptive neuro-fuzzy inference system (ANFIS)

In this work, it is assumed that ambiguous the inference system contains two inputs x_1, x_2 and one output, z as shown in Figure 5(b). The network used in this study accepts up to six inputs parameter as the following:

$$[x1, x2, ..., x6]=[H, D, F, L, ESDD, C] \quad (11)$$

The overall output as the summation of all incoming parameter can be expressed as:

$$O_5^i = \sum_i \overline{w_i} f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} = U_{FO}(H, D, F, L, ESDD, C) \quad (12)$$



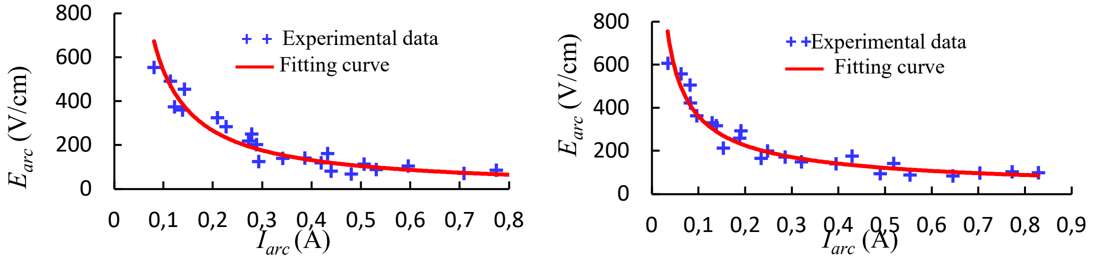
(a) (b)

Figure 5. Schematic algorithm of, (a) ANN model, (b) ANFIS

6. RESULTS AND DISCUSSION

6.1. E_{arc}-I_{arc} characteristics and arc constant ‘N’ and ‘n’

The parameters data of arc for the highest arc length were recorded for both porcelain and glass insulators and shown in Figure 6. As can be observed, the arc voltage gradient of insulators as a function of the arc current giving exponential relationship.



(a) (b)

Figure 6. *Earc -Iarc* characteristic of, (a) Glass insulator LXY-70, (b) Porcelain XP-70

The mathematical relation of E_{arc}-I_{arc}curves can be expressed as:

$$E_{arc(A)} = 62.53\, I_{arc(A)}{}^{-0.73} \text{(for Type A),and } E_{arc(B)} = 76.02\, I_{arc(B)}{}^{-0.68} \text{(for Type B)} \qquad (13)$$

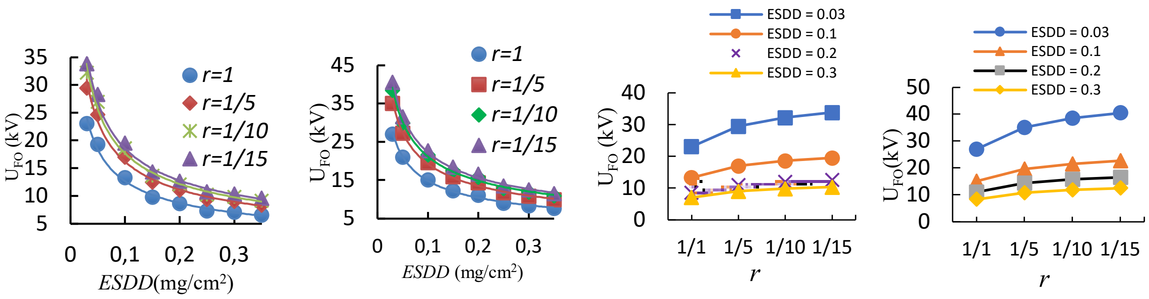
The calculated arc constants (*N, n*) values of the tested insulators are summarized in Table 4.

Table 4. Constant arc values for tested insulators

Type	Experimental		Computation	
	N	n	N	n
L XY- 70	63.08	0.725	62.53	0.73
XP-70	75.37	0.68	76	0.68

6.2. Flashover voltage $U_{FO}$for polluted insulators

Figure 7(a, b) show the plot of the relationship between flashover voltage and ESDD obtained from the experimental results under different non-uniform pollution conditions. The curve has been fitted all cases by using the exponential function expressed in (7). The results of fitting curve of *x* value and y value were acquired under various non-uniform contamination conditions and uneven contamination degree *r*, as tabulated in Table 5. It can be observed from Figure 7(c, d) and Table 5 that the uneven contamination degree *r* has incredible effect on the flashover voltage U_{FO}. The U_{FO} voltage increases with an increase in the pollution ratio in the area near the high voltage terminal on the bottom surface of the insulator for both insulators. On the other hand, with decrease of *r,* the maximum of flashover voltage U_{FO} of uniformly polluted insulator increases by 46.75% and 50.22% for the glass porcelain insulator respectively.



(a) (b) (c) (d)

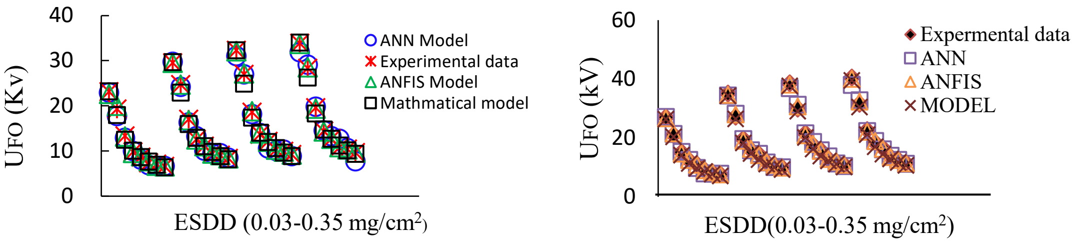
Figure 7. The trend of U_{FO}under non-uniform pollution conditions

6.3. Validation of model and artificial intelligence (AI) results

The proposed AI model is compared with Experimental and mathematical model. The comparison of the ANN, ANFIS, mathematical model and the experiment results under different non-uniform pollution condition is given in Figure 8. The comparison of different flashover voltage results obtained for the porcelain insulator under uniform pollution case is shown in Figure 9. The flashover value, U_{FO} obtained from the artificial intelligence models and mathematical is compared in Figure 9. As can bee seen, the result are at good agreement to the experimental data by other researcher [4].

Table 5. Curve fitting results of U_{FO}under different non-uniform pollution

r	1/1			1/5			1/10			1/15		
	x	y	c	x	y	c	x	y	c	x	y	c
L XY- 70	3.65	0.54	1	4.66	0.54	1.28	5.1	0.54	1.4	5.36	0.54	1.47
XP-70	4.55	0.512	1	5.91	0.512	1.3	6.493	0.512	1.43	6.835	0.512	1.5



(a) (b)

Figure 8. The comparison of AI technique models by experimental and mathmatical model results, (a) Glass, (b) Porcelian

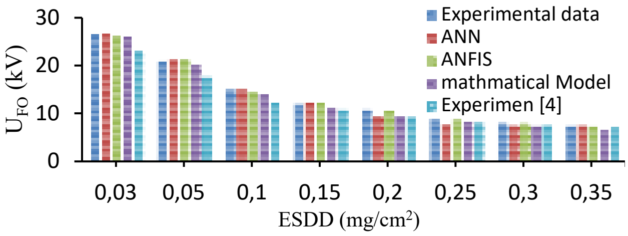


Figure 9. Comparison of U_F under uniform pollution condition

7. CONCLUSION

This paper discusses the experimental approach and the least square simulation technique to achieve the suitable values of arc constants N and n and two artificial intelligence techniqueswere designed for the estimation of flashover voltage in artificially non-uniform polluted glass and porcelain insulators. The mathematical model based to the geometric characteristics of the insulator, ESDD and constant of arc was applied and validated using experimental flashover voltage results. Therefore, the determination of the constants of arc allows the simulation of the critical conditions for the flashover voltage. Various of non-uniform pollution cases 1:1, 1/5, 1/10 and 1/15 have considered in this work, these pollution conditions have a great influence on the U_{FO}. An artificial neural network has been applied to the measurement results and a good agreement has been achieved with the high determination of coefficients which is more than 97%.

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